

Chapter 6

Water Treatment

6-1. Introduction

The purpose of water treatment is to do whatever is necessary to render a raw water suitable for its intended use. Since both raw water qualities and intended uses vary, water treatment must be carefully tailored to fit individual situations. Even the most basic forms of water treatment require some operator time on a daily basis. More sophisticated plants may require almost constant attention. Thus, it behooves the designer of any water supply system, especially a small one, to give a great deal of attention to operational complexity when selecting water treatment techniques. From this viewpoint, the best treatment is no treatment at all. That is, the best approach is to locate a water source that requires no treatment. When the intended use is human consumption, regulatory requirements effectively limit such sources to existing water supply systems. Thus, any new source is probably going to require some treatment. When high-quality groundwater is available, it may be possible to limit treatment to disinfection. On the other hand, even the highest quality surface water will require turbidity removal in addition to disinfection. This is a major reason why groundwater is often preferred over surface water. Additional treatment will be required to deal with special problems such as tastes, odors, hardness, etc. Designers of small water systems should keep treatment facilities as simple as possible. Table 6-1 lists the BAT for drinking water contaminant removal. It is included only to indicate that removal of various constituents can be complex. However, the removal and the degree of removal are specified by state and local regulations and should be adhered to rather than this manual. As has already been pointed out in this manual, the degree of regulation for removal of contaminants can be affected by the quantity of water consumed.

a. Assumptions. In this chapter various operations and processes commonly used in water treatment are introduced and briefly discussed. Attention is deliberately focused on the typical needs of small water systems; thus, no attempt has been made to address every possible situation. The general approach is to consider typical treatment problems, briefly describe the most likely alternative means of treatment, alert the reader to the principal requirements and most important design considerations, and point out sources of more specific information, should such be desired. A fairly extensive list of references is included in Appendix A; however, no attempt has been made to present an exhaustive literature review. Many of the publications cited have rather complete lists of references on the particular subjects covered. Thus, the reader may be led to the desired information through a series of reference

citations. Cookbook approaches to design are not offered. It is assumed that the intended use of the water is human consumption, that the raw water quality is known, and that raw water is available in sufficient quantities to allow for bench and pilot scale treatability studies. Chapter 3 discusses water quality requirements, common constituents of water, and the regulatory framework for protection of the safety and integrity of public water supplies. Emphasis is given to treatment required of typical ground and surface waters. However, many of the references cited also deal with more exotic problems. The USEPA "Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations" (1977a) is a good general reference on water treatment.

b. Nomenclature. Many water treatment professionals make a distinction between "operations" and "processes." Because this distinction is somewhat arbitrary and is not rigorously adhered to, some confusion is inevitable. As a rule, "operations" involve the application of physical principles and forces, while "processes" involve chemical reactions or biological activity. Therefore, screening, straining, and settling technically are operations, while chlorination and chemical coagulation are processes. Sometimes no clear distinction is readily apparent. Examples include adsorption of organic substances onto activated carbon and granular media filtration. Thus, some authors use the terms virtually interchangeably. This approach is used in this manual.

c. Design basis. Water treatment is an old, highly specialized, and largely empirical technical field that is strongly influenced by considerable conservatism with respect to protection of public health and the monetary investments of the public in water supply systems. Therefore, the field has traditionally been slow to accept new technology. However, increased research activity, motivated largely by public interest in the linkage between environmental factors and the quality of life (especially health), serves to make it quite likely that water treatment practices unknown today will be commonplace in the near future. In the meantime, the design of water treatment facilities is heavily influenced (dictated in many cases) by regulatory requirements based on previously successful practice. In these circumstances the job of the designer is often to find the most economical design that satisfies the regulatory agency with jurisdiction. However, many water treatment techniques can be modeled in the laboratory, or on a pilot scale, with relative ease. It is recommended that, where appropriate, such tests be performed and that the results, along with regulatory guidelines, serve as the basis for design. Information relative to bench and pilot scale studies is widely available from sources including Clark, Viessman, and Hammer (1977), Fair, Geyer, and Okun (1966b), Hudson (1981), Sanks (1978), and Weber (1972). Many engineers understand water treatment fairly well from a mechanistic or operational point of view, but have little appreciation for the

Table 6-1
Best Available Technologies for Drinking Water Contaminant (adapted from AWWA)

Contaminant	Conventional Processes	Specialized Processes
	Microbials	
<i>Cryptosporidium</i>	C-F SSF DF DEF D	
<i>E. coli</i>	D	
Fecal coliforms	D	
<i>Giardia lamblia</i>	C-F SSF DF DEF D	
Heterotrophic bacteria	C-F SSF DF DEF D	
<i>Legionella</i>	C-F SSF DF DEF D	
Total coliforms	D	
Turbidity	C-F SSF DF DEF D	
Viruses	C-F SSF DF DEF D	
	Inorganics	
Antimony	C-F ¹	RO
Arsenic	NA	
Asbestos (fibers/1>10 µm)	C-F ¹ DF DEF CC	IX RO
Barium	LS ¹	IX RO
Beryllium	C-F ¹ LS ¹	AA IX RO
Bromate	DC	
Cadmium	C-F ¹ LS ¹	IX RO
Chlorite	DC	
Chromium (total)	C-F LS ¹ (Cr III) ¹	IX RO
Copper	CC SWT	
Cyanide	CL2	IX RO
Fluoride		AA RO
Lead	CC SWT PE LSLR	
Mercury	C-F ²⁺¹ LS ¹	RO ² GAC
Nickel	LS ¹	IX RO
Nitrate (as N)		IX RO ED
Nitrite (as N)		IX RO

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Note: Abbreviations used in this table: AA - activated alumina; AD - alternative disinfectants; AR - aeration; AX - anion exchange; CC - corrosion control; C-F - coagulation-filtration; CL2 - chlorination; D - disinfection; DC - disinfection-system-control; DEF - diatomaceous earth filtration; DF - direct filtration; EC-enhanced coagulation; ED - electrodialysis; GAC - granular activated carbon; IX - ion exchange; LS - lime softening; LSLR - lead service line removal; NA - not applicable; OX - oxidation; PAP - polymer addition practices; PE - public education; PR - precursor removal; PTA - packed-tower aeration; RO - reverse osmosis; SPC - stop prechlorination; SWT - source water treatment; SSF - slow sand filtration.

¹ Coagulation-filtration and lime softening are not BAT for small systems.

² Influent <= 10 µg/L.

³ Sum of the concentrations of bromodichloromethane, dibromochloromethane, tribromomethane, and trichloromethane.

Table 6-1. (Continued)

Contaminant	Conventional Processes	Specialized Processes
Inorganics (continued)		
Nitrite & Nitrate (as N)		IX RO
Selenium	C-F(Se IV) ¹ LS ¹	AA RO ED
Sulfate		IX RO ED
Thallium		AA IX
Organics		
Acrylamide	PAP	
Alachlor		GAC
Aldicarb		GAC
Aldicarb sulfone		GAC
Aldicarb sulfoxide		GAC
Atrazine		GAC
Benzene		GAC PTA
Benzo(a)pyrene		GAC
Bromodichloromethane		EC
Bromoform		EC
Carbofuran		GAC
Carbon tetrachloride		GAC PTA
Chloral hydrate		EC
Chlordane		GAC
Chloroform		EC
2,4-D		GAC
Dalapon		GAC
Di(2-ethylhexyl) adipate		GAC PTA
Di(2-ethylhexyl) phthalate		GAC
Dibromochloromethane		EC
Dibromochloropropane (DBCP)		GAC PTA
Dichloroacetic acid		EC
p-Dichlorobenzene		GAC PTA
o-Dichlorobenzene		GAC PTA
1,2-Dichloroethane		GAC PTA
1,1-Dichloroethylene		GAC PTA
cis-1,2-Dichloroethylene		GAC PTA

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Table 6-1. (Continued)

Contaminant	Conventional Processes	Specialized Processes
Organics (continued)		
trans-1,2-Dichloroethylene		GAC PTA
Dichloromethane (methylene chloride)		PTA
1,2-Dichloropropane		GAC PTA
Dinoseb		GAC
Diquat		GAC
Endothall		GAC
Endrin		GAC
Epichlorohydrin	PAP	
Ethylbenzene		GAC PTA
Ethylene dibromide (EDB)		GAC PTA
Glyphosate		OX
Haloacetic acids ¹		
(Sum of 5; HAA5)		EC
-		EC+GAC
Heptachlor		GAC
Heptachlor epoxide		GAC
Hexachlorobenzene		GAC
Hexachlorocyclopentadiene		GAC PTA
Lindane		GAC
Methoxychlor		GAC
Monochlorobenzene		GAC PTA
Oxamyl (vydate)		GAC
Pentachlorophenol		GAC
Picloram		GAC
Polychlorinated biphenyls (PCBs)		GAC
Simazine		GAC
Styrene		GAC PTA
2,3,7,8-TCDD (dioxin)		GAC
Tetrachloroethylene		GAC PTA
Toluene		GAC PTA
Toxaphene		GAC

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Table 6-1. (Concluded)

Contaminant	Conventional Processes	Specialized Processes
Organics (continued)		
2,4,5-TP (silvex)		GAC
Trichloroacetic acid		EC
1,2,4-Trichlorobenzene		GAC PTA
1,1,1-Trichloroethane		GAC PTA
1,1,2-Trichloroethane		GAC PTA
Trichloroethylene		GAC PTA
Total Trihalomethanes ³	AD PR SPC	
(sum of 4)		
-		EC
-		EC+GAC
Vinyl chloride		PTA
Xylenes (total)		GAC PTA
Radionuclides		
Beta-particle and photon emitters	C-F	IX RO
Alpha emitters		
-	C-F	RO
Radium 226+228		
Radium 226	LS ¹	IX RO
Radium 228	LS ¹	IX RO
Radon	AR	
Uranium	C-F ¹ LS LS ¹	AX

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chemistry that makes many of the processes work. A deeper understanding of fundamental process chemistry can lead to designs that are more economical and effective than those developed solely by application of traditional criteria. Benefield, Judkins, and Weand (1982) is especially useful in this regard. General information on design of water treatment facilities is plentiful (AWWA 1971, 1990; Clark, Viessman, and Hammer 1977; Culp and Culp 1974; Fair, Geyer, and Okun 1966b; Hamann and Suhr 1982; Hammer 1975; Hudson 1981; Merritt 1976; Nalco Chemical Company 1979; Sanks 1978; Steel and McGhee 1979; and Weber 1972). Some specific guidance for Corps of Engineers projects is presented

in TM 5-813-3. Regulatory agency personnel and publications are excellent sources of information pertinent to specific problems and local requirements. Much can be learned by observing existing water treatment plants, looking over operating records, and discussing operational problems with knowledgeable plant personnel. Other major information sources include the AWWA Standards, EP 310-1-5, and equipment manufacturers and suppliers. Problems specific to small water systems are discussed in Clark (1980), Clark and Morand (1981), Hansen, Gumerman, and Culp (1979), Lehr et al. (1980), Morand et al. (1980), and Stevie and Clark (1980, 1982).

6-2. Disinfection

Disinfection involves the removal, destruction, or inactivation of pathogenic (disease-causing) organisms, and will be discussed first since it is often the only form of treatment required for small water systems. The effectiveness of disinfection is generally determined indirectly via enumeration of coliform organisms in the treated water (paragraph 3-4d and 3-7). Ideally none should be present. The USEPA proposed regulation for disinfectants and disinfection by-products in 1994. It is anticipated that the practice will continue to change, especially in response to maximum allowable levels of suspected health-risk by-products. Changes in operations and treatment will continue as new developments in technology, scientific knowledge, and regulations occur.

a. Alternative methods. Disinfection may be accomplished by a number of means, including the application of

- (1) Heat (e.g., pasteurization).
- (2) Radiation (e.g., ultraviolet light).
- (3) Heavy metals (e.g., silver).
- (4) Oxidizing chemicals (e.g., chlorine, iodine, hydrogen peroxide, ozone).

Each method has its uses, but economics and public health considerations favor the use of oxidizing chemicals for potable water treatment. Within this category, chlorine has been and probably will continue for many years to be the disinfectant of choice for most water supply systems, especially the smaller ones (AWWA 1982; Hoff and Geldreich 1981; and Rice et al. 1981). When disinfectants are applied to surface waters and groundwaters under the influence of surface waters, the product of *C* and *T*, i.e., residual disinfectant concentration times the disinfectant contact time, must meet minimum requirements as specified in tables provided by the USEPA. In addition, consideration must be given to the development of disinfectant by-products. State regulatory agencies should be contacted for current regulatory levels for any and all by-products. The resulting concentrations may have an impact on the disinfectant selected.

b. Chlorination.

(1) Advantages and disadvantages. Some advantages of disinfection with chlorine are listed below:

- (a) Relatively low cost.
- (b) Ease of application.
- (c) Proven reliability.

- (d) Easy detectability.
- (e) Residual disinfecting power.
- (f) Familiarity with its use.
- (g) Used for other treatment purposes (e.g., oxidation).

The principal disadvantages of chlorination are that in some cases undesirable tastes and odors may be produced (e.g., reactions with phenols) and chlorination of some organic substances produces compounds known or suspected to be hazardous to human health. One group of such compounds, the trihalomethanes or THMs (e.g., chloroform), are already the subject of Federal regulation (para 3-4d(4), Kavanaugh et al. 1980; Krabill 1981; Singer et al. 1981; and Vogt and Regli 1981).

(2) Chemistry of chlorine. When chlorine is added to water, a variety of reactions may take place, but not all at the same rate. The difference between the amount of chlorine added to a water (the dosage) and the amount remaining at any given time (the residual) is a measure of the amount that has reacted and is referred to as the "demand." The chlorine residual is, therefore, a measure (though not a perfect one) of the potential for continuing disinfection. The products of reactions between chlorine and ammonia (NH_3) or the ammonium ion (NH_4^+) are of special interest because they possess some disinfecting ability of their own. Collectively these products are called "chloramines" and are often referred to as "combined available chlorine." It is necessary to distinguish the combined available chlorine residual from the "free available chlorine residual" (i.e., chlorine that has reacted only with the water itself), because the effectiveness of the latter is much greater than that of the former in the pH range (6 to 9) of interest in water treatment. Chlorine chemistry is covered very well in most water supply textbooks (e.g., Clark, Viessman, and Hammer 1977; Fair, Geyer, and Okun 1966b; Hammer 1975; Sanks 1978; and Steel and McGhee 1979).

(3) Required residual. Regulatory requirements vary considerably, but adequate disinfection of relatively clear water (turbidity < 5 NTU) can usually be accomplished by maintaining a free available chlorine residual of 1 mg/L for at least 30 minutes at a pH < 8. Higher residuals and/or longer contact periods will provide an increased level of protection from pathogens. Reductions in contact time and/or high pHs should be compensated for with higher residuals. A residual of 0.2 mg/L free available chlorine throughout the distribution system will minimize risks associated with possible recontamination of treated water; however, state regulations call for minimum and perhaps maximum values at various points within the water treatment system.

(4) Alternative forms of chlorine. Chlorine is available in several forms. A brief discussion of those commonly used in water treatment is presented below.

(a) Chlorine gas. Liquified chlorine gas is by far the most popular form of chlorine for use at larger water treatment plants. It is relatively inexpensive, especially when purchase in railroad tank car lots is feasible. However, chlorine gas is extremely hazardous and special precautions such as a separate chlorination room or facility, floor level ventilation, and provision of safety equipment such as gas masks must be undertaken when it is used. As a result, gas chlorination is often unsuitable for small water systems, although several equipment suppliers have small gas chlorinators available in their product lines.

(b) Calcium hypochlorite. Calcium hypochlorite is a dry powder or granular material that is widely used for small installations such as home swimming pools. The commercial form has a long shelf life and is safer to handle than chlorine gas (although all forms of chlorine used for disinfection are hazardous to some degree), but contains a significant insoluble, inert fraction. Typical products are 60 to 65 percent available chlorine by weight. When calcium hypochlorite is used to disinfect water, the dry form is mixed with water and the insoluble fraction is allowed to settle. The liquid is then drawn off and used as a stock solution to disinfect the water supply. Failure to separate the liquid from the insoluble residue may result in clogging or otherwise damaging equipment. For small systems, this process may be a disadvantage since significant operator time is required. The other major disadvantage is cost. On an equivalent basis calcium hypochlorite is up to six times as expensive as chlorine gas in small 150-pound cylinders.

(c) Sodium hypochlorite. Sodium hypochlorite is probably the best form of chlorine for small water systems. It is commercially available as a clear liquid containing between 12 and 17 percent available chlorine and is marketed in containers as small as 2 L (1/2 gal). Some very small water systems can use household bleaches such as Clorox or Purex, which are dilute (about 5 percent available chlorine) solutions of sodium hypochlorite. The major advantages of sodium hypochlorite are that it is relatively safe to use, and since it is already a liquid, little handling or processing is required prior to use. Costs are similar to those of calcium hypochlorite. The major disadvantages of sodium hypochlorite are that it has a half-life of approximately 90 days so it cannot be kept for long periods and it presents a chlorine gas danger if mixed with acid or ferric chloride.

(5) Hypochlorinators. Several types of hypochlorite solution feeders, called hypochlorinators, are available. The best type for small water systems is the positive displacement pump variety. These devices make use of a small metering

pump that can be precisely adjusted to deliver the hypochlorite solution at a given rate against a wide range of resisting pressures. Typically, operation of the metering pump is synchronized with that of the water pump so that when water is flowing, the chlorine solution is automatically fed into either the suction or discharge piping in the proper proportion. Duplicate units should be provided so that disinfection will not be interrupted. Most positive displacement hypochlorinators are electrically operated, but water-powered models are also available. It is good practice to provide some type of sensing device on the chlorine solution tank that will set off an alarm or automatically shut down the water pumps when the solution level drops too low. Suction and aspirator feeders are also available to feed chlorine solutions, and tablet chlorinators that use pelletized calcium hypochlorite are marketed by several firms. Tablet, aspirator, and suction chlorinators are usually more difficult to control and less dependable than the positive displacement type. Chemical compatibility must be evaluated for all components such as pump and pump parts, solution tanks, and piping/tubing. The specifications and drawings should require that the manufacturer certify his equipment for the proposed service.

(6) Chlorine dosage. The proper chlorine dosage depends upon a number of factors including the

- (a) Chlorine demand.
- (b) Contact period.
- (c) Residual.
- (d) Temperature.
- (e) pH.

Unfortunately there is no way to determine the required dosage directly without experimentation. However, under normal conditions, no more than 2 or 3 mg/L will be required. Higher demands, shorter contact periods, lower temperatures, and/or pH above about 8 will increase the required dose. Compliance with the disinfection rule must be achieved as required for various treatment techniques as determined by state environmental authorities.

(7) pH control. pH is a very important factor in the control of chlorination. When sufficient chlorine (gas or hypochlorite) is added to a water to produce a free available residual, a chemical equilibrium is established between the hypochlorous acid molecule (HOCl) and the hypochlorite ion (OCl⁻). This equilibrium is controlled by pH. The two forms of free available chlorine are present in roughly equal amounts at a pH around 7.7. At a lower pH the acid predominates, and at a higher pH the ion is more prevalent. The third possible form of free available chlorine, the Cl₂, does not exist in

solution at pH levels high enough to be of interest in water treatment. (Note: if pH drops to as low as 2 or 3, gas may be evolved. This is an extremely hazardous situation.) The equilibrium between acid and ion is established regardless of the form in which the chlorine is added (gas or hypochlorite); however, the net effect on pH is not the same. Addition of the gas will destroy alkalinity and lower the pH, while addition of hypochlorite will tend to raise the pH. It is important to hold the pH in the 5 to 8 range if possible, since the acid molecule is a far more effective disinfectant than the ion. Thus, it may be necessary to add a chemical such as sodium bicarbonate or sulfuric acid along with chlorine to adjust the pH to the desired range.

(8) Superchlorination-dechlorination. For some small water systems, it is difficult or impossible to ensure an adequate contact time for ordinary chlorination. In these cases it is possible to superchlorinate, that is, to add more chlorine than would ordinarily be necessary, and then remove the excess (dechlorinate) prior to use. Dechlorination can be accomplished chemically by addition of a reducing agent such as sodium sulfite, sodium bisulfite, or sodium thiosulfate, or by activated carbon adsorption. However, chemical methods are difficult to control precisely enough to leave a consistent residual, and activated carbon adsorption can be expensive. Where possible it is probably better to provide additional contact time (e.g., by making the pressure tank on hydro-pneumatic systems bigger or by storage reservoir addition and using a repumping operation) than to attempt superchlorination-dechlorination.

(9) Chlorine-ammonia treatment. When chlorination produces undesirable tastes and odors, or when the production of chlorinated organic compounds must be minimized, chlorine-ammonia treatment may be used. The controlled addition of both substances together results in a combined available chlorine (chloramine) residual that does not react with phenols to produce taste and odor problems and does not produce chloroform or similar compounds. Chloramines are much less effective as disinfectants than either hypochlorous acid or hypochlorite, but they are very persistent and can provide some level of protection for an extended period. The cost and operational complexity of this technique should be evaluated versus other measures such as carbon adsorption for precursor removal.

(10) Chlorine dioxide. Chlorine dioxide ClO_2 , is a powerful oxidant that has excellent germicidal properties, is unaffected by pH in the range normally encountered in water treatment, and does not react with ammonia. It has been used successfully for control of tastes and odors, especially those produced by phenols, but is seldom used in the United States for disinfection. Chlorine dioxide does not react with water; thus its chemistry is quite different from that of the more commonly used forms of chlorine. Its principal advantage for

potable water disinfection is that it apparently can oxidize organic substances without producing halogenated hydrocarbons, such as chloroform. However, it is a very dangerous gas that must be produced onsite, and the health effects of possible by-products of its use are unknown or poorly defined. Thus, for the present, chlorine dioxide is unlikely to be the disinfectant of choice for small water systems, although low-capacity generation systems are available. An excellent discussion of chlorine dioxide chemistry, generation, use, etc., is presented by White (1978).

c. Iodination. Iodine is an excellent disinfectant, but is much more expensive than chlorine (as much as 20 times) and has possibly deleterious health effects, especially for unborn children and individuals with thyroid problems. While the extent of these effects is not fully known, it seems reasonable that iodine can be safely used as a disinfectant for public water supplies serving only a transient population, or in short-term (up to 3 weeks) emergency situations. The combination of unfavorable economies and possible health effects makes continuous use of iodine unwarranted (Folks 1977; Weber 1972).

d. Ozonation. Ozonation for disinfection of public water supplies has been practiced in Europe for many years and is gaining popularity in the United States. Ozone, O_3 , does not form trihalomethanes or other substances presently known to have deleterious health effects. Thus, the process is attractive for large systems where a potential trihalomethane problem exists. There are three principal disadvantages of ozonation for disinfection of small water supplies. One is that ozone is so unstable that no residual can be maintained. This can be overcome by using ozone as the primary disinfectant and maintaining a residual with chlorine-ammonia treatment, for example. This process is far too complicated for most small water systems. A second problem is that ozone must be generated onsite. This complicates operation and maintenance problems and is energy intensive as well. Thirdly, ozonation is simply too expensive for many small systems. Ozone can be a safety hazard, and appropriate safety requirements must always be developed for each site.

e. Ultraviolet radiation. Ultraviolet (UV) radiation has been recognized for many years as having germicidal properties, and has been proposed for disinfection of water supplies since the early twentieth century. Commercially available UV radiation devices intended for water treatment are composed of a quartz sleeve housing one or more low-pressure mercury vapor lamps that radiate at a wavelength in the 250- to 260-nm range. The lamps themselves are similar to fluorescent bulbs without the coating to convert UV radiation to longer wavelength visible light. UV radiation disinfects by destroying the cell, or interfering with normal growth and development. In order to be effective, the radiation

must be incident on each organism. Thus, suspended particles (e.g., turbidity) can shade and protect organisms. Substances such as iron compounds, phenols, other aromatic organic compounds, etc., are effective UV absorbers and can also reduce efficiency. The process can be designed to work automatically, requires minimal contact time, and produces no known undesirable by-products, and overdosing is not possible. However, the penetrating power of the radiation is low, the lamps slowly lose effectiveness, no residual disinfecting power is produced, there is no rapid test of effectiveness, efficiency is limited by the factors noted above, the equipment is expensive, and electrical power consumption is high. Presently, the use of UV radiation for disinfecting public water supplies is limited to very small systems, processing low-turbidity waters, having low concentrations of absorbing substances, when residual disinfecting ability is unimportant.

6-3. Iron Removal

Problems commonly associated with iron in water and possible removal techniques are introduced in paragraph 3-8g. The specific problem observed is related to the valence state of the iron. Ferrous iron Fe^{+2} is soluble in water and can cause taste problems. Ferric iron Fe^{+3} is much less soluble and tends to form precipitates that vary in color from yellow to brown to red. These particles make the water unsightly and can cause staining of plumbing fixtures, interfere with cleaning and washing activities, and impart an unpleasant taste to the water. In most natural waters, the ferrous form is readily oxidized to the ferric form by contact with molecular oxygen. Certain attached filamentous bacteria (*Crenothrix* and *Leptothrix*) derive energy by oxidizing iron and storing the oxidized form in their structure. These organisms are especially troublesome to water systems because they take up residence in piping systems. Occasionally clumps of organisms, in the form of gelatinous masses, break away and are entrained in the flow. Thus, periodic severe iron problems may result. The diversity of iron problems is such that control techniques must be tailored to fit specific situations. Therefore, an important first step is to determine what form the iron is in and what range of concentration can be expected. Secondly, the possibility that the iron is present as a result of corrosion should be investigated if applicable. It is generally better to control the corrosion process than remove the iron after corrosion occurs.

a. Polyphosphates. When the iron is in the ferrous (dissolved, colorless) state and the concentration is no more than about 3 mg/L, the most convenient approach may be to simply mask the problem by adding polyphosphates such as sodium hexamethaphosphate. These compounds act as chelating agents to sequester the iron prior to precipitation. Therefore, they should be applied before oxidation occurs. The sequestering process may be thought of simply as preventing the iron from entering into the reactions that produce precipitates. The iron is not removed from the water.

Polyphosphate doses of 1 mg/L to 5 mg/L per mg/L iron present are typical. The process is simple and requires only a polyphosphate solution tank and feed systems similar to that used for hypochlorination systems (paragraph 6-2b(5)). As a bonus, polyphosphates may help control corrosion. However, hexamethaphosphates can begin to break down within 24 hours or less, reverting to an orthophosphate which has no sequestering capability. Also, orthophosphates can serve as a nutrient to water system bacteria and other microbes. Hence, retention time within the water system is a critical element for deciding on its use.

b. Ion exchange. Small amounts of ferrous iron may be removed by ion exchange type water softeners (paragraph 6-5b). However, ferric iron must not be present or severe fouling of the exchange media can occur. When this technique is used, manufacturers' recommendations with respect to the maximum allowable iron concentration and installation and operation of the exchanger should be followed rigorously. Maximum limits may range upward to 5 or 10 mg/L. However, experience in some Corps Districts has been that levels greater than 1 mg/L can cause resin fouling if iron bacteria contamination is present.

c. Oxidation-filtration. The most popular methods of iron removal involve oxidation of the iron by aeration, chlorination, or treatment with potassium permanganate, followed by some form of filtration. The rate of oxidation via aeration or chlorination is faster at higher pH. Thus, it may be necessary to adjust the pH to 7 or above to achieve satisfactory results. In larger plants a sedimentation step is often used to remove the settleable fraction of the precipitate and take some load off the filters. The filters used may be the gravity type, such as slow or rapid sand filters, or may be pressure operated. Pressure filters are commonly used for small systems, especially when double pumping can be avoided. The so-called oxidizing filter is a pressure type that is frequently employed. The media in oxidizing filters usually consists, at least in part, of natural greensand and zeolite coated with oxides of manganese. These oxides promote rapid oxidation by serving as catalysts, or by actually entering into reactions, and may also serve as adsorption sites for ferrous ions. Frequently, a separate layer of granular material, such as sand or anthracite coal, is provided to act as a roughing filter to remove precipitates and prevent clogging of the oxidizing layer. This type of filter requires occasional backwashing. The zeolite and coating can be reactivated by occasional regeneration with potassium permanganate. Typical flow rates are up to 20 L per minute per square meter ($\text{L}/\text{min}/\text{m}^2$) (5 gallons per minute per square foot ($\text{gal}/\text{min}/\text{ft}^2$)) of nominal filter surface area. A sustained flow of at least 30 to 40 $\text{L}/\text{min}/\text{m}^2$ (8 to 10 $\text{gal}/\text{min}/\text{ft}^2$) of filter area must be available for a duration of several minutes to provide adequate filter bed expansion during backwashing. Volume expansions up to 40 percent may be required for

cleaning. All types of filters, but especially pressure filters, perform better in continuous operation than in situations where frequent start/run/stop cycles are required. Thus, it may be beneficial, from the standpoint of filter effluent quality, to provide enough treated water storage capacity to minimize the number of on/off cycles required per day. Typically, if alkalinity is less than 100 mg/L as CaCO_3 , manganese zeolite process for iron removal is not recommended without increasing the alkalinity.

(1) *Aeration.* Oxidation via aeration is frequently used for surface waters. The air may be applied through small bubble diffusers by a low-pressure blower, by spraying the water into the air, or by allowing the water to trickle down over a multiple-tray aerator. A typical design calls for three or four trays covered with coke or some other medium having a large surface area. The water is sprayed onto the top tray and allowed to trickle down over the lower trays. The high-surface-area medium serves to increase the area of the air/water interface and thus promote oxidation. The process also removes undesirable gases such as carbon dioxide and hydrogen sulfide. If the pH is maintained above about 7, the process can be very effective, especially when followed by filtration. An advantage of aeration is that the system cannot be overdosed; thus, precise operator control is not required. Devices for introducing oxygen under pressure are available for use with pressurized groundwater systems. However, it may not be desirable to oxygenate these waters since it will promote corrosion.

(2) *Chlorination.* Oxidation of iron with chlorine is effected by a number of variables including pH, chlorine dose, reaction time, mixing conditions, etc. Generally the process proceeds much slower than oxidation by permanganate. In some cases it may be necessary to superchlorinate and then reduce the residual following filtration. When this is required, granular activated carbon filters may be used to remove both the particulates and the excess chlorine. This can be quite expensive since the carbon will require occasional regeneration. For small plants, it may be less expensive to replace the carbon rather than regenerate onsite. The chlorine may be fed by solution feeders (paragraph 6-2b(5)). Superchlorination-dechlorination is discussed in paragraph 6-2b(8).

(3) *Potassium permanganate.* Ferrous iron is readily oxidized to the ferric form by potassium permanganate. The permanganate can be added to the water by solution feeders similar to hypochlorinators (paragraph 6-2b(5)). In theory, a potassium permanganate dose of 1 mg/L will oxidize 1.06 mg/L of iron; however, in practice it may be possible to use less than the theoretical dose. The reaction with permanganate is many times faster than that with chlorine, and is easily controlled since a small excess of permanganate

produces a slight pink color. An additional advantage of this method is that pH within the range of about 5 to 9 does not significantly affect the reaction rate. The combination of permanganate addition, a short reaction time (contact tank), and an oxidation (greensand) filter is referred to as a potassium permanganate, continuous regeneration operation. If extra permanganate is added, it regenerates the greensand media. The process is most effective when the iron content of the water is fairly constant, but can work well if properly operated when the iron concentration varies up to 1.5 and 2.5 mg/L. In principle, where excess ferrous iron exceeds the KMnO_4 injection level, the greensand oxidizes the iron. Hence good operator control should require the checking for occasional pink downstream of the filter to assure complete recharge.

d. Iron bacteria. Iron bacteria problems can be effectively controlled by a rigorous chlorination program in concert with one of the other techniques discussed above. When iron concentrations are very low, continuous removal may not be needed and periodic superchlorination may be all that is required. One must always ensure that components transferred from one water system to another have been adequately disinfected prior to reinstallation to prevent the potential spread of iron bacteria and other organisms.

e. Summary. Iron removal problems can be frustrating since processes that work to control one form may be relatively ineffective against other forms. Thus, the importance of correctly identifying the true nature of the problem cannot be overemphasized. Pilot or bench scale studies can be very helpful in selecting a dependable process. For small water systems, dependability and ease of operation are key factors in design.

6-4. Manganese Removal

Manganese is much less common than iron, but is removed by essentially the same processes. Problems associated with manganese are discussed in paragraph 3-8h. Removal of manganese is complicated to a degree since oxidation proceeds most rapidly at a pH of around 9.5, especially when aeration or chlorination is used. Treatment with 2 mg/L or less potassium permanganate per mg/L of manganese is effective for oxidation to the insoluble form. Permanganate oxidation followed by an oxidation filter is a dependable removal process. Many times, iron and manganese problems are found together. Unlike the continuous regeneration operation, where the main objective is to remove iron, if the water contains only manganese or manganese with small amounts of iron to be removed, intermittent regeneration is recommended. Intermittent regeneration uses a KMnO_4 solution to fill, hold, and recharge the greensand filter after a specified quantity of water has been processed.

6-5. Hardness Removal

Hardness, which is usually composed almost entirely of calcium and magnesium, is introduced in paragraph 3-8f. The two basic methods of hardness removal (softening) are chemical precipitation and ion exchange. The former is widely used at larger plants, but is so operationally complex and expensive that it is almost never used for small installations.

a. Purpose. Hardness, at levels normally encountered, is not considered a health problem; therefore, removal is not mandatory. Thus consideration must be given to whether there is any real need to remove it. Such a question calls for the careful balancing of a combination of aesthetic and economic factors. Most people who are not used to hard water would probably prefer that water with a total hardness of more than about 125 mg/L as calcium carbonate be softened prior to use. However, unless public acceptance is a problem, it is difficult to justify softening a water containing a total hardness less than about 200 mg/L as calcium carbonate. Above about 300 mg/L as calcium carbonate, some removal is almost always necessary to protect equipment and piping systems.

b. Ion exchange softening. From an operational standpoint, ion exchange softening is a very simple process. A typical softener looks very much like a pressure filter in that it is a cylindrical container enclosing a packed bed of granular material. This material is called the exchange medium, and in modern softeners is usually a synthetic organic substance, such as polystyrene, formed in small beads. Typical bead diameters range from about 0.3 to 1.2 mm with the vast majority (95 percent or so) falling in the 0.4- to 0.8-mm region. Other types of exchange media are also marketed, and the nomenclature can be confusing since descriptive terms are used rather loosely. Originally, naturally occurring zeolite was the only choice. When technology to manufacture synthetic media came available, the term synthetic zeolite was used to describe some of the products. The term resin is also frequently used in reference to some types of media.

(1) Operation. Regardless of the specific medium used, it is a material that has many chemically active surface sites to which metallic ionic species are attracted. For freshly prepared (or regenerated) media these sites are predominantly occupied by monovalent species such as hydrogen or, more commonly in the case of potable water treatment, sodium.

(a) Removal. The water to be treated is passed through the softener at rates ranging from about 8 to 20 L/min/m² (2 to 5 gal/min/ft²) of nominal exchanger surface area. As the water moves through the bed of medium, divalent ions in the water such as calcium and magnesium replace the monovalent species (sodium) in the medium because of their stronger affinity for the medium sites. Thus, divalent ions are “exchanged” for monovalent ions that do not contribute to

hardness. There is no change in the electrochemical balance since one divalent ion replaces two monovalent ones. The process continues until the medium is “exhausted.” At this point, few surface sites are available and divalent ions begin to break through into the treated water effluent. When this occurs, the medium must be regenerated. Ion exchange softeners are not intended to act as filters for suspended solids, although the beads are small enough to trap such material. Thus, it is important to pretreat turbid waters (turbidity 5 NTU) prior to softening. The media are not selective for calcium and magnesium; therefore, ferrous iron can be removed. However, most manufacturers recommend maximum concentrations of iron that should not be exceeded in the feed water, since excessive iron will tend to foul the media, reduce efficiency, and increase head loss through the bed.

(b) Regeneration. Regeneration is accomplished by passing a strong solution of the appropriate monovalent ion through the exchanger for a short period, or by “soaking” the medium in such a solution. For sodium type exchangers (the most common), a 10 to 15 percent solution of sodium chloride is used. Although less expensive grades are available, a purified salt should be used for regeneration. The next best choice would be a very clean rock salt. Typically rock salt contains considerable trash and has a significant insoluble fraction that will tend to clog the exchanger. An acid solution would be used for a hydrogen type medium. The exchange process reverses because of overwhelming numbers of monovalent ions. After rinsing, the exchanger is again ready for use. The regeneration process can take from a few minutes to as much as an hour. The process can operate fully automatically (regeneration initiated by a timer or water meter), semi-automatically (manual start for regeneration), or manually. The method of regeneration must be considered based on the frequency of “operator checks” and the amount of usage.

(c) Efficiency. Modern ion exchange media are quite durable and can be regenerated an almost unlimited number of times. The frequency with which regeneration is needed is a function of the capacity of the medium (i.e., the theoretical mass of ions that can be exchanged per unit volume of medium), the hardness of the water, the flow rate, and the efficiency of the regeneration process. Since regeneration is essentially a mass action phenomenon, there is a decreasing rate of return for increasing the regenerate concentration. Thus, it may be economical to regenerate with a weaker solution and do so more often, than to use a more concentrated solution and achieve a greater percent recovery of the surface active sites. However, small system design may be controlled more by operational convenience than by economics. The desired efficiency and frequency of regeneration are key design factors.

(2) Exchange capacities. The history of ion exchange is such that the commonly used units of expression may be

confusing. For example, the capacity of a given type of exchange medium is often expressed as so many grains of hardness per cubic foot, and manufacturers' literature may express concentrations in grains per gallon. One grain is equal to 1/7000 pound or about 0.0684 gram. One grain per gallon is approximately 17.1 mg/L.

(3) Split treatment. The nature of the ion exchange process is such that it is not possible to design a unit to remove less than 100 percent of the hardness applied. In practice some bleedthrough may occur, but this is insignificant in the case of potable water treatment. Thus, softeners may be assumed to be completely effective until the medium is exhausted, significant breakthrough occurs, and regeneration is required. Since there is no need to completely soften a public water supply, only a portion of the total flow need pass through the softener. The remainder may be bypassed and then mixed with the softened water to achieve the desired level of hardness. Typical combined product water should have a total hardness of 50 to 100 mg/L as calcium carbonate.

(4) Wastes. The principal difficulty with ion exchange softening of small water supplies is that waste regenerate solution is produced when the medium is regenerated. The volume of this wastewater is relatively small, but a suitable means of disposal must be available. Unfortunately, municipal wastewater systems may not accept this material. The high sodium concentration may make septic tank disposal unacceptable also since, for certain soils, sodium may be exchanged for the naturally occurring multivalent metals usually present and reduce permeability. The significance of this potential problem is quite variable. Disposal of high-strength sodium-recharge water should be coordinated with environmental regulators. If sodium-containing wastewater disposal becomes a problem, then a hydrogen form cationic resin should be evaluated.

6-6. Taste and Odor Removal

Undesirable tastes and odors in drinking water can stem from a variety of sources (Zoeteman, Piet, and Postma 1980). For groundwaters, a common cause of complaint is hydrogen sulfide, which produces a "rotten egg" odor. For surface waters, the problem is usually related to the metabolic activity of algae, actinomycetes, or other organisms, or contact with decaying vegetative matter. Reactions between chlorine and certain organic substances (e.g., phenols) may produce a noticeable taste or odor. Chlorine itself may be objectionable to some users, but in normal concentrations most people become acclimated quickly. Occasionally, taste and odor problems are related to contamination by industrial, municipal, or domestic wastes. This is potentially the most serious situation since some contaminants deleterious to public health may be presumed to be present. Excessive concentrations of iron can produce metallic tastes that are unacceptable to many

people. Taste and odor problems are mentioned briefly in paragraph 3-8e.

a. Reporting units. Dealing with tastes and odors can be troublesome and frustrating for water system operators because the problems frequently are of an intermittent nature, the sensitivity of exposed individuals varies greatly, and control or treatment must be geared to the specific cause if success is to be expected. The problem is complicated to a significant extent because there is no reliable test procedure except to empanel a group of individuals to smell and/or taste the water. (Taste and odor are so closely linked that it is usually impossible to separate them. However, some substances, e.g., inorganic salts, may produce a taste without any noticeable odor.) The reporting unit commonly used for odors (and associated tastes) is the TON. TON is defined as the dilution factor required before an odor is minimally perceptible. Thus a TON of 1 (i.e., no dilution) indicates essentially odor-free water (paragraph 6-12a).

b. Removal. The design of taste and odor removal processes should not be undertaken until the cause of the problem has been identified and bench or pilot testing has been performed to determine the effectiveness of alternative techniques. Commonly used approaches are discussed below.

(1) Management practices. Often the best control procedures are to develop an alternative supply, or manage the source to minimize the problem. The latter approach is especially appropriate for surface waters when biological activity (algae, decaying vegetative matter, etc.) is the source of the tastes and odors. Typical management practices include aquatic weed control programs such as deepening or varying the water level of reservoirs, dredging to remove growing plants and debris, and chemical treatment. Chemical treatment programs are also very effective against algae. Land use management in the watershed area is an effective tool that may be used to control weed and algae problems by limiting the nutrients entering the body of water to a quantity insufficient to stimulate excessive growth. Control of land use can also be used to protect against contamination by industrial, municipal, domestic, or agricultural wastes.

(2) Aeration. Tastes and odors associated with some substances can be reduced or eliminated by aeration. Surface waters are especially amenable to this method since aeration can usually be integrated into the treatment scheme without great difficulty. The principal removal mechanism is usually stripping, although some oxidation may also occur. Good success with algal metabolites, volatile organic compounds, and hydrogen sulfide is frequently achieved. Even when not totally successful, aeration may substantially reduce the load on other treatment processes such as adsorption. Aerators similar to those used for oxidation of iron (paragraph 6-3c(1)) can be used.

(3) Adsorption. Granular activated carbon filters are useful in removing tastes and odors caused by substances that will readily adsorb onto the carbon. Typical units look somewhat like pressure filters, but the term “filter,” which is used by many equipment manufacturers and suppliers, is somewhat of a misnomer since the usual object is to remove dissolved, rather than suspended, substances. However, when filtration is needed, it may be possible to combine the processes. Carbon adsorption is effective against a variety of substances, including organic decay products, residual chlorine and chlorination by-products, pesticides, and some dissolved gases. Synthetic adsorbents are available that are capable of similar or superior performance in specific cases, and that can effectively remove hydrogen sulfide. The sorptive qualities of various carbons and synthetic adsorbents differ substantially. Thus, bench or pilot scale testing is needed before a final design can be accomplished. When the adsorbent is finally exhausted, replacement is necessary since onsite regeneration is impractical for most small systems. In very low flow applications, disposable cartridge type units may be sufficient. Flow rates through granular activated carbon beds generally range from 8 to 20 L/min/m² (2 to 5 gal/min/ft²) of nominal bed surface area. Backwashing is needed occasionally to dislodge solids that may accumulate. Since activated carbon is very effective for dechlorination, it will generally be necessary to disinfect following adsorption. For surface water treatment, application of powdered activated carbon may be feasible. In this process the carbon is added to the water, mixed with it, and then allowed to settle. Filtration is required to remove fines. This approach is especially good when the taste and odor problem occurs only at certain times of the year. Little added expense is involved, except that directly associated with carbon addition, since settling and filtration are usually used for surface water treatment anyway.

(4) Oxidation. Oxidizing agents such as chlorine and potassium permanganate also find application in taste and odor control. However, before the decision is made to use chlorine, consideration should be given to the need for subsequent dechlorination and the possible production of undesirable chlorinated organic compounds. In addition, adequate detention time is needed to ensure process effectiveness. Feeding chlorine for taste and odor control may be accomplished by solution feeders such as the hypochlorinators used for disinfection (paragraph 6-2b(5)). When chlorine is used to control sulfides, insoluble precipitates may be formed that can be effectively removed by pressure filters similar to those used for iron removal (paragraph 6-3c).

6-7. Stabilization and Corrosion Control

Stabilization and corrosion control are closely related topics and will, therefore, be discussed as a unit.

a. Stabilization. A water is considered stable if it tends neither to deposit nor dissolve solid calcium carbonate. For a given water, stability is a function of the calcium ion concentration, total alkalinity, and pH. Lime may be added to adjust (increase) all three variables simultaneously and is frequently used for this purpose. Other chemicals including sodium carbonate (soda ash), sodium hydroxide (caustic soda), and carbon dioxide are occasionally used. As a general rule, the desirable characteristics of a finished water include calcium and alkalinity concentrations that are similar and in excess of 40 mg/L as CaCO₃, a pH no higher than about 9.0 to 9.3 (depending upon the magnesium concentration), and the potential to deposit 4 to 10 mg/L of CaCO₃. A thin, hard layer of this precipitate makes an excellent coating that protects the insides of pipes, pumps, hydrants, etc., from corrosion. A water that dissolves CaCO₃ is considered corrosive. A water that deposits excessive amounts of CaCO₃ may clog pumps and appurtenances and reduce the carrying capacity of pipelines substantially. Thus, it is important to produce a reasonably stable water. The magnesium concentration is important because magnesium hydroxide (Mg(OH)₂) tends to deposit in excess in hot-water lines and appliances if the concentration is greater than about 40 mg/L as CaCO₃. These deposits dramatically affect the performance and expected life of such items as water heaters. Detailed discussions of stabilization and simplified methods for estimating required chemical doses are widely available (Benefield, Judkins, and Weand 1982; Merrill and Sanks 1977a, 1977b, 1978; and Sanks 1978).

b. Corrosion control. In general, it is not possible to completely protect a water system from corrosion. However, careful control of water quality can reduce the rate at which corrosion occurs quite substantially.

(1) Water quality. Corrosion is usually associated with the following factors. It should be noted that these factors are often interrelated.

- (a) Low pH.
- (b) Low mineral content.
- (c) Low alkalinity.
- (d) High dissolved oxygen concentration.
- (e) High carbon dioxide concentration.

Most groundwaters do not contain high concentrations of oxygen. Therefore, it is best to limit the opportunity for the water to pick up oxygen as it is pumped, processed, and distributed.

(2) Neutralization. The usual cause of corrosiveness of groundwater is the presence of high concentrations of carbon dioxide and the resulting low pH. While it is possible to strip most of the carbon dioxide out by aeration, this is usually not practiced for groundwaters because the oxygen introduced in the process also promotes corrosion, and double pumping may be required. A better approach is to neutralize the excess carbon dioxide chemically. Either sodium bicarbonate or sodium carbonate (soda ash) is useful for this purpose since they are readily available, are relatively inexpensive, are highly soluble, do not add hardness, produce no residue, and are fairly safe to handle. The neutralizer solution may be injected into the flow, or directly into the well using the same type of feed equipment used for hypochlorites (paragraph 6-2b(5)). In fact, the solution may be mixed with hypochlorite and fed simultaneously if desired. This practice reduces equipment costs, but the mixture must be prepared carefully to ensure proper dosage of both chemicals. Application directly to the well offers some potential advantages where it is practical, since protection will be afforded to pumps and other submerged equipment. Other chemicals such as sodium hydroxide (caustic soda), calcium hydroxide (hydrated lime), or calcium oxide (quick lime) may also be used, but may pose operational problems or require special equipment (e.g., lime slaker). Use of sodium bicarbonate or soda ash will increase the sodium concentration of the water. Whether this is undesirable will depend upon the background sodium concentration and the intended use for the water. Excessive sodium intake does appear to be related to hypertension and associated cardiovascular problems, at least for some individuals. An alternative method of neutralization is to pass the water through a bed of clean limestone chips. The corrosive water will slowly dissolve the chips and thus be neutralized. This process can be troublesome since the chips will need occasional replacement, backwashing will be occasionally required to keep the bed from clogging, and a relatively long contact time is required to achieve neutralization. In any case, the design of neutralization processes should be preceded by laboratory experimentation and evaluation to establish required doses, contact times, optimal solution strengths, etc.

6-8. Turbidity Removal

Turbidity (paragraph 3-8c) removal is almost always required when a surface water source is used, but is almost never needed for groundwaters. The particles that cause turbidity (mostly clay) are very small (1-200 mm effective diameter) and are affected much more by surface chemical and electrical phenomena than by gravity. Thus, neither settling nor filtration is an effective removal technique unless preceded by treatment to encourage the particles to agglomerate to substantially larger sizes. This preliminary treatment is commonly referred to as coagulation and/or flocculation. The thrust of this section is to alert the reader to important design considerations and not to present detailed procedures. Turbidity removal is covered in

almost every text on the subject of water supply engineering. Examples are presented in AWWA (1971, 1990), Benefield, Judkins and Weand (1982), Clark, Viessman, and Hammer (1977), Fair, Geyer, and Okun (1966b), Hammer (1975), Hudson (1981), Sanks (1978), Steel and McGhee (1979), and Weber (1972).

a. Coagulation/flocculation. The exact definitions attached to the terms coagulation and flocculation vary depending upon who is using them. Water chemists generally use the term coagulation to describe the processes that make particle agglomeration possible, and restrict the meaning of the word flocculation to the actual physical agglomeration itself. However, it is often difficult to distinguish the two in an operational setting such as a treatment plant. Therefore, design engineers and water treatment operating personnel often use the terms rather loosely.

(1) Coagulation. Several chemicals, usually called coagulants or flocculants, are available to stimulate the aggregation of smaller particles to a size that can be economically removed from water by settling and filtration. By far the most popular for potable water treatment is filter alum, a commercially available form of aluminum sulfate. Typical water treatment practice calls for sufficient alum to be added to the water to cause the precipitation of aluminum hydroxide. This precipitate, in conjunction with various other aluminum hydrolysis products that also may be formed, acts to neutralize surface electrical charges on the particles that cause turbidity, and enmesh or entrap the particles in the resulting sludge. The process proceeds best if the alum is introduced with intense, short-term (1-minute) mixing, followed by longer term, gentle mixing. What water chemists refer to as coagulation occurs during the brief, but intense, mixing period which design engineers usually call flash or rapid mixing. Energy to provide the mixing usually comes from high-speed mechanical stirrers; however, in-line static mixers are also effective and are useful where it is practical to inject the alum directly into a pipeline. In some cases effective mixing can be accomplished by injecting alum just upstream of the suction side of a centrifugal pump. Alum is commercially available in dry powder, granule, or lump form, and as a liquid. For small plants, liquid alum is usually most practical. Equipment of the same type used for hypochlorites (paragraph 6-2b(5)) may be used to feed liquid alum. If purchase of liquid alum is undesirable, the operator can manually mix the dry form with clean water. This requires care since it is important to have a solution of consistent concentration. Alum feed solutions should be mixed at concentrations recommended by the chemical manufacturer. The concentration of the original stock solution affects the aluminum species present.

(2) Flocculation. The longer term, gentle mixing period is called flocculation. The time required for flocculation (i.e., particle agglomeration and enmeshment) to occur is a function

of mixing intensity and the nature of the particles. The mixing must be intense enough to encourage particle collisions, but not intense enough to shear aggregated particles apart. The principal design parameters are the mean velocity gradient, usually given the symbol G , and the mixing time, t . Optimal performance is usually obtained with G in the range of 30-60 L/sec, mixing time varying from 10 to 45 minutes, and $G*t$ (dimensionless) ranging from 10^4 to 10^6 . Detailed information for calculating G for various mixers are presented in typical water supply engineering texts (AWWA 1971; Benefield, Judkins, and Weand 1982; Clark, Viessman, and Hammer 1977; Fair, Geyer, and Okun 1966b; Hammer 1975; Sanks 1978; Steel and McGhee 1979; and Weber 1972). Mechanical, paddle-wheel type mixers are very commonly used. The coagulant dose necessary to induce flocculation cannot be calculated directly and, thus, must be determined experimentally. The "jar test" procedure, a simple test used for this purpose, is described in texts such as those referenced above and in Hudson (1981).

(3) Coagulation/flocculation aids. Many times experimentation will reveal that the use of a small amount (usually less than 1 mg/L) of some high molecular weight polymeric substance (referred to in the water treatment industry simply as a "polymer" or "polyelectrolyte") in conjunction with alum will substantially improve performance, reduce the amount of alum required, and reduce the volume of sludge produced. Cationic (positively charged) polymers have generally been most effective, but a specific polymer should be chosen only after extensive experimentation. In some cases polymers are used alone (especially for low-alkalinity waters and in conjunction with direct filtration); however, this can be quite expensive. Coagulant aids other than polymers (e.g., bentonite clay and activated silica) are occasionally used. Many water chemical manufacturers provide onsite services to water system authorities at no cost in hope of developing new customers. The manufacturer's representative comes onsite with various polymers and will bench-test various chemicals, polymer aids, etc., at differing dosages to determine optimum performance levels. It is recommended that several water chemical suppliers be invited (at different times) onsite to evaluate their best product and optimal dosage. All information developed should remain privileged to the owner and supplier. This competition will encourage the recommendation of the best chemicals and optimum dosage levels at the most favorable pricing.

(4) Other coagulants. Coagulants other than alum are occasionally used in potable water treatment. Examples include ferric chloride, ferric sulfate, and magnesium carbonate. The ferric salts work in a manner very similar to alum. The use of magnesium as a coagulant requires high pH (10.8 to 11) and is only rarely practiced. Because of the lower costs for these types of chemicals, a polymer manufacturer will usually not test these types of chemicals. If the possibility for usage of

lower cost chemicals exists, then an independent evaluation by water treatment engineers or laboratory technicians may be warranted.

(5) pH control. Control of pH is very important when alum is used as a coagulant. The addition of alum to water, and the subsequent chemical reactions that occur, tend to destroy alkalinity and lower pH. This is somewhat unfortunate since the alum coagulation/flocculation process as described in (3) above works best in the pH range from about 5.5 to 8.5. If insufficient natural alkalinity is available to buffer pH into this range, lime, soda ash, or some other substance must be added as a supplement. Fortunately, the optimal pH range is compatible with that required for disinfection by chlorination. Solution feeders such as those used for hypochlorination may be used to add additional alkalinity. Coagulation with the iron salts, mentioned in (4) above, is somewhat less sensitive to pH than is coagulation with alum.

b. Sedimentation. Conventional settling facilities provided at larger turbidity removal plants are often long, narrow (4 or 5 to 1 length to width ratio) rectangular basins with theoretical detention times in the range of 3 to 6 hours at the design flow rate. Most regulatory agencies specify a minimum detention period and a maximum areal (or surface) overflow rate. Typical values for the latter are 20 000 to 30 000 L (500 to 800 gallons) applied per day per square meter of nominal tank surface (or floor) area. For small plants, high-rate settling devices using inclined tubes or plates are very popular. These devices are available in considerable diversity from many equipment manufacturers and suppliers. Both steeply inclined (1 rad (60 degrees) to horizontal) and relatively flat (0.2 rad (10 degrees) to horizontal) designs have been used successfully. The latter are perhaps more common. The use of high rate devices results in reduced space requirements (hence their almost universal use for package type plants) without significant increase in required operator skill, effort, or time. The most important factors in design of settling facilities are to get the water into the basin with a minimum of turbulence, provide an adequate settling period under quiescent flow conditions (never more than a 0.3-m (1-ft) per minute bulk fluid velocity), provide storage for sludge, provide a means to remove sludge periodically, and get the water out of the basin with a minimum of turbulence and reentrainment of sludge. Fulfilling this last requirement generally requires a weir to take the overflow off the tank. Most regulatory agencies insist on a weir overflow rate of not more than 250,000 L (20 000 gallons) per day per meter of weir length. A second weir, or pipe, is usually provided to limit the depth over the outflow weir to that corresponding to the design flow rate. Some solids will, of course, not settle. The velocity of flow in the pipe or channel leading to the filters should be kept low enough (say 0.6 m (2 ft) per second) to keep from shearing these particles into even smaller pieces.

c. *Flocculator/clarifiers.* A number of equipment manufacturers market combination flocculator/clarifier devices often called solids contact units or upflow tanks. These units incorporate the coagulant feed, rapid mixing, flocculation, and clarification (settling) steps into a single tank by means of pipes, valves, baffles, etc. The principal advantages of this approach are reductions in space, detention time, and piping requirements. An important disadvantage is that the regulatory agency with jurisdiction may find such devices unacceptable. Typical devices are described in detail in AWWA (1971) and Steel and McGhee (1979).

d. *Filtration.* Sedimentation is less than 100 percent effective for removal of suspended particles, even when preceded by coagulation and flocculation. Thus, filtration is virtually an absolute requirement for any surface water. Detailed graphics depicting various type of filters are presented in most standard texts (AWWA 1971; Clark, Viessman, and Hammer 1977; Fair, Geyer, and Okun 1966b; and Steel and McGhee 1979).

(1) General. The filters most commonly used for small surface water treatment systems are the pressure type. The filter medium most often used is sand having an effective size of 0.4 to 0.6 mm and uniformity coefficient of about 1.3 to 1.7. A 600- to 750-mm- (24- to 30-in.-) deep bed supported by 450 to 600 mm (18 to 24 in.) of hard, rounded, graded gravel (2.4- to 57.2-mm (3/32-in. to 2-1/4-in.) diameter) is common for conventional rapid sand filters. Sometimes as much as one-half the filter bed depth (about 380 mm (15 in.)) is occupied by crushed anthracite coal or activated carbon having a uniformity coefficient of 1.8 or less and an effective size of 0.6 to 0.8 mm. Units such as these are called dual media filters. Occasionally three or more different types of media may be used in what are known as mixed media filters. The rationale behind dual and mixed media filters is that the backwashing process distributes the sand in a rapid sand filter such that the smallest grains move to the top of the bed and the largest grains move to the bottom. Since a downflow operational mode is used during filtration, the water encounters the smallest grains (and openings) first. Therefore, most particles are removed in a narrow band near the top of the bed. This causes head loss to build relatively rapidly. If larger grains of some less dense material are also placed in the bed, backwashing will move them to the top of the bed. Thus, while each "layer" is still stratified with its smallest grains at the top, the overall effect is larger grains underlain by smaller grains. With this arrangement, the filter can operate longer at a given flow rate before backwashing is required, or the filter can work at a higher rate without significant loss in product water quality, or perhaps both, compared to a conventional rapid sand filter. The mixed media filter (three or four different densities) is simply a logical extension of the dual media concept. Since the filters represent the last barrier to

suspended contamination before the water enters the distribution system, regulatory agencies tend to hold to very conservative design criteria. Typical flow rates are 80 L/min/m² (2 gal/ min/ft²) of nominal filter area for rapid sand filters, although double or triple this value is frequently allowed for dual or mixed media filters. There are several optional methods of filter flow control. For small systems where only one filter is active at a time, some type of constant rate of flow controller on the effluent line works well. The venturi controller is a proven design. At least two filters should be provided. A backwash system capable of delivering treated water at a flow rate of 600 to 800 L/min/m² (15 to 20 gal/min/ft²) of nominal filter area for about 20 minutes is needed to clean the filters. Some filter designs (mostly proprietary) employ other backwashing techniques that may have different requirements. Regulatory agencies generally have very specific requirements with respect to piping, underdrains, backwashing, etc., as well as filtration rates and filter media. Major design factors include filtration rate, filter media, regulatory requirements, desired effluent quality, allowable head losses, and backwashing frequency. As a general rule, effective backwashing is the key to successful rapid sand, dual media, or mixed media filtration. Logsdon and Fox (1982) and Trussell et al. (1980) pertain directly to filtration and may be of interest in addition to the general turbidity removal references cited above.

(2) Slow sand filters. Slow sand filters are generally not used following coagulation, flocculation, and settling. However, for very high quality surface waters, and in cases where groundwaters must be filtered, slow sand filters may be a good choice. Their use for community water supplies may, however, require special regulatory agency approval. Slow sand filters operate by gravity, as do rapid sand filters, but they are never backwashed. When the head loss through a slow sand filter becomes excessive (the exact value depends on the particular design), the filter is taken off line, drained, and allowed to dry. The *schmutzdecke* (layer of debris, trapped particles, etc.) is then removed, or the surface is at least raked, and the filter is returned to service after subsequent development of a new *schmutzdecke*. Several cleanings can be performed before the replacement of media is required. The active part of a slow sand filter is the *schmutzdecke* and the top 25-50 mm (1-2 in.) of sand. The remaining sand acts mostly as a backup or factor of safety, although a few particles may be removed deep within the bed. Thus, before the filter can be returned to service, it must be "ripened." This is accomplished by loading the filter and either wasting the effluent or recycling it to another filter until a new *schmutzdecke* is developed. Thus, at least two filters, and preferably three, should be provided. A typical filter is composed of a 1220-mm- (48-in.-) deep bed of homogeneously packed sand, having an effective size of 0.2 to 0.4 mm and a uniformity coefficient of 2.5 or less, supported by 250 to 300 mm (10 to 12 in.) of graded (5 to 76 mm

(3/16 in. to 3 in.) in diameter) gravel. Each filter should be equipped with a head loss gauge, an adequate underdrain system, and a cover to prevent algae growth in the water being filtered. Typical flow rates are around 3.26 to 3.67 L/min/m² (0.08 to 0.09 gal/min/ft²) of nominal filter surface area. A water depth of about 1.2 m (4 ft) above the sand surface is typical. A rate-of-flow controller may be used on the filter discharge to ensure a more or less constant production rate throughout a filter run (may last several days to a month or more). Slow sand filters work best when the average raw water turbidity is 10 NTU or less; however, occasional peak turbidity up to 25 NTU can be handled. The filters should not be used for waters containing more than about 0.3 mg/L iron or 0.05 mg/L manganese.

(3) Direct filtration. The direct filtration process (AWWA 1980b; Logsdon and Fox 1982; McKormick and King 1982; and Trussell et al. 1980) is mostly of interest for low-turbidity waters. In direct filtration, coagulants are used, but the sedimentation step (and sometimes even a portion of the flocculation step) is omitted. Thus, the filter is the sole means of suspended solids removal. Direct filtration is a relatively new process and may not be acceptable to many regulatory agencies, especially for small plants. The process is most applicable when raw water turbidity is consistently 10 NTU or less. In these cases the only coagulant required may be one of the polymers previously discussed (*a*(3) above). Direct filtration is accomplished using equipment similar to a rapid sand filter.

e. Package plants. The use of a “package plant” should be fully investigated in situations where surface water treatment is required. Package plants are preengineered, usually prefabricated, treatment plants available in a variety of sizes (40 L/min (10 gal/min) to several million liters per day) from several manufacturers. In many cases they can be delivered to the site virtually intact, set up, connected to an electrical power source and the required piping, and placed into operation in a matter of days if necessary. As a general rule, the technology used is proven, and excellent performance can be expected provided that the manufacturer’s recommendations with respect to operation and maintenance are rigorously followed. Some package plants are equipped with process control systems that automatically adjust chemical doses based on raw and finished water turbidity and pH, monitor flow rates, indicate equipment breakdowns, etc. Such a system, when properly maintained, can reduce operator time and result in more efficient use of chemicals. Since the units are preengineered and pre-fabricated (to varying degrees), they can be considerably less expensive than equivalent custom designed and constructed facilities. Most manufacturers have technical support personnel that can work with clients to adapt their units for special local conditions. The industry is highly competitive, however, and a particular plant should not be

selected without careful consideration of the design, maintenance requirements, possibly exaggerated advertising claims, and technical trouble shooting support offered by the manufacturer or supplier. Most package plants designed for surface water treatment applications employ mechanically mixed flocculators, high-rate settlers (tube or plate type), and gravity filtration devices similar to rapid sand filters. Solids contact units and pressure filters are offered by some manufacturers. Considerable information concerning package plant performance and cost is available in the literature (Clark 1980; Clark and Morand 1981; Hansen, Gumerman, and Culp 1979; Morand et al. 1980; and Stevie and Clark 1980). In most cases where package plants have failed to produce an acceptable finished water, the fault has been inadequate operation and maintenance, not plant design. For package plant projects, the manufacturer should be required to provide an appropriate amount of onsite training and system operation instructions, separate from operation and maintenance manuals, to the system owners’ potential operator.

f. Waste disposal. Typically, turbidity removal results in two waste streams, filter backwash water and sludge. The two wastes are actually very similar except that the former is much more dilute than the latter. In some cases, especially for some types of package plants and in the case of direct filtration, only one “composite” waste stream is produced. Principal components of both types of wastes are the suspended particles removed from the water along with coagulant precipitates that are formed. As a rule, the wastes are not particularly objectionable in terms of odor. If a municipal sewer is available, it may be possible to dump filter backwash water and sludge directly to the waste treatment system. Where both filter backwash and sludge are produced, it may be possible to reduce the volume of the waste substantially by recycling the backwash water to the plant and ultimately disposing of all captured solids in the sludge. It may also be possible to hold filter backwash and sludge in a thickener and haul the thickened sludge away occasionally. It is usually not acceptable to return water treatment wastes to the water source (Reh 1980).

6-9. Total Dissolved Solids Removal

On rare occasions, available sources of water will contain excessive amounts of total dissolved solids (TDS). This problem is most likely to be encountered in groundwaters found in the midwestern and southwestern United States and in surface waters (and some groundwaters) in coastal areas. The chemical species that contribute most frequently to TDS are calcium, magnesium, sodium, bicarbonate, chloride, and sulfate. Unfortunately, it is very difficult to establish fully rational maximum acceptable concentrations for TDS because the various chemical species that may be involved have

different effects. In addition, public acceptance of high-TDS waters is quite variable. Common complaints include a salty taste and laxative effect. When possible neither chloride nor sulfate should exceed 250 mg/L and TDS should be no more than 500 mg/L. These values correspond to the maximum contaminant levels recommended by the USEPA pursuant to the SDWA (paragraph 3-5). Methods for removal of TDS include ion exchange and several membrane processes. Among the latter category, reverse osmosis (RO) appears to offer the best prospect for small water systems.

a. Reverse osmosis. When high-TDS water is separated from fresher water by a semipermeable membrane, the natural tendency is for the fresh water to diffuse through the membrane as if it were under pressure, and dilute the high TDS. This hypothetical pressure is called the osmotic pressure, and the overall process is known as osmosis. If sufficient pressure is applied on the high-TDS side of the membrane, the process can be reversed and water from the high-TDS region will diffuse through the membrane and thereby be purified. Thus, fresh water or permeate is produced. This process, reverse osmosis, has been developed for small water systems by equipment manufacturers.

(1) Typical units. Commercially available reverse osmosis units vary mostly in the pressures and membrane materials used, and are suitable for flow rates of a few hundred to a million liters per day. Many designs are modular in concept and can be put together readily to treat much larger flows. A typical unit is composed of a high-pressure pump (1400 to 10 000 kilopascals (200 to 1500 pounds per square inch)) and a membrane module. Several membrane materials including nylon and cellulose acetate are available. In the typical unit the membrane is in the form of bundles of hollow fibers. Major factors to consider in design are first cost, operation and maintenance costs (which include pumping and membrane replacement), feed water quality, temperature, salt rejection (i.e., effectiveness of the membrane in containing the dissolved solids), water recovery (i.e., efficiency with respect to permeate production to feedwater flow), waste disposal, and required pretreatment. The last category is very important since hardness, iron, manganese, organic matter, sulfides, and chlorine may tend to foul or damage membranes. Proper pretreatment (which obviously can be extensive and expensive) is probably the single most important factor in successful RO treatment. This can be especially important for units with low water recovery (the typical range is from 20 to 95 percent). If water recovery is 50 percent, for example, the pretreatment units must be sized for a flow rate twice the actual production rate.

(2) Efficiency and waste disposal. Salt rejection rates vary considerably, but 90 to 99 percent removal is not uncommon. An exception is nitrate, which may typically be removed with an effectiveness of only 50 to 80 percent. The

reject water from an RO unit may thus contain around 90 percent of the total feed water TDS in a flow that can vary from 5 to 80 percent of the feed water flow. Disposal of these wastes can be a serious problem and should be considered early in the design process. In most cases the disposal method must be approved by both water and wastewater oriented regulatory agencies. When designing RO facilities, it is important to work closely with equipment manufacturers and suppliers since they are a major source of basic information, and common practice is to purchase preengineered, manufactured units ready to install. Most are available complete with automatic control systems. Many water supply texts present discussions of RO, as well as other membrane processes (ultrafiltration, dialysis, and electrodialysis) that may be of interest (Clark, Viessman, and Hammer 1977; Fair, Geyer, and Okun 1966b; Hammer 1975; Lehr et al. 1980; Sanks 1978; Steel and McGhee 1979; and Weber 1972). The quality of the feed water has a major impact on production rate; thus, expected variations in raw water quality must be considered. Temperature is also important, with higher solvent recovery, but shorter membrane life, associated with higher temperatures. pH can also be important and, depending largely upon the specific membrane chosen, it may be necessary to adjust the feed water pH.

b. Ion exchange. Ion exchange may also be used for TDS removal. The process is similar to that previously described for softening (paragraph 6-5b) except that both cationic and anionic exchange media are used. Since removal of all TDS is usually desired, hydrogen form cationic media and hydroxide form anionic media are normally used. The former may be regenerated with strong acid and the latter with strong base. Major operational problems are associated with pretreatment, regeneration (the solutions are very corrosive), waste disposal, and limited durability of most types of anionic media. The advice of equipment manufacturers and suppliers should be heeded when selecting ion exchange devices and media.

6-10. Color Removal

True color (i.e., color due to dissolved substances) is often very difficult to remove. Apparent color (color due to suspended substances) is generally removed along with turbidity (paragraph 6-8). A brief discussion of color is presented in paragraph 3-8d. True color can occasionally be removed by oxidation or adsorption in a manner somewhat similar to removal of iron and manganese (paragraphs 6-3 and 6-4) and tastes and odors (paragraph 6-6). Color problems can sometimes be controlled at the source if the precise cause can be determined. Paragraph 6-11, which deals with removal of dissolved organic substances, may be relevant to color removal as well. Since the presence of true color may indicate industrial contamination, the source of any color problem should be fully identified.

6-11. Control of Organic Substances

Organic substances may contribute to a variety of problems including taste, odor, and color, and some are known to have adverse health effects. It is known that hundreds and perhaps thousands of organic compounds may be present in any given natural water, even groundwater previously thought to be relatively uncontaminated. The real environmental and public health significance of most of these substances remains unknown, however. This is especially true of long-term effects of exposure to the very low concentrations typically found in water supplies. Considerable attention has been focused on pesticides and on one group of chlorinated hydrocarbons called trihalomethanes (e.g., chloroform), and more recently haloacetic acids (HAA). In many, perhaps most, cases the removal of organic compounds, especially dissolved compounds, from drinking water is expensive, requires skillful operation, and can be monitored only with the aid of complicated and expensive analytical techniques. This type of activity is not readily compatible with typical small water system operation. Recognizing the difficulty and expense in monitoring very low concentration, the USEPA provides for specific techniques for water treatment in the case of detected contaminants.

a. Trihalomethanes. Precursors of trihalomethanes (THMs) exist in most natural waters and are converted to THMs by halogenation, for example by chlorination as usually practiced at water treatment plants. A maximum contaminant level for THMs is specified in the drinking water standards. Control of THMs and their precursors is a newly developing field. However, several possible approaches have already proven somewhat effective. These are included as BAT processes and would include the controls described below.

(1) Watershed management. The best approach to control of THMs, and all organics for that matter, is to find a water source that does not contain significant concentrations of them, and then protect that source from subsequent contamination by careful watershed management. This is not a feasible approach for most larger cities, but can be very practical for small communities. Control of land use in the watershed area can be very effective against synthetic chemicals of industrial or agricultural origin. In addition, control of the algal population in the reservoir (if there is one) can be of major importance since algae are responsible for some THM precursors.

(2) Conventional treatment. In many instances THMs can be effectively controlled by eliminating precursors (prior to chlorination) by strict attention to the conventional treatment processes such as coagulation, flocculation, settling, and filtration. Optimization of the performance of these processes, coupled with no chlorination of untreated water, will often suffice. When the situation dictates that raw waters be disinfected, some method other than chlorination (e.g., ozonation or chlorine dioxide treatment) can be used. The

effectiveness of this approach is widely documented (Kavanaugh et al. 1980; Singer et al. 1981; and Vogt and Regli 1981).

(3) Alternative disinfection. Disinfectants other than chlorine may be used in water treatment. While this will solve the problem of formation of chlorinated organics during treatment, there may be undesirable side effects, including increased costs and lower residual disinfecting power. Alternative disinfectants are introduced in paragraph 6-2a (see also Hoff and Geldreich 1981 and Rice et al. 1981).

(4) Aeration. Volatile organic compounds can sometimes be transferred from the liquid to the gaseous phase and removed from water by aeration. The process is similar to that described for iron and taste and odor problems, except that packed tower aeration systems are more predominant than aeration trays (paragraphs 6-3c(1) and 6-6b(2)). Care must be used to avoid picking up contaminants from the air (Kavanaugh and Trussell 1980).

(5) Chemical oxidation. In some cases, THM precursors can be removed by chemical oxidation in concert with more conventional processes. Permanganate and ozone may be useful for this purpose (Glaze et al. 1982; Peyton et al. 1982; Rice et al. 1981; and Singer, Borchardt, and Colthurst 1980).

(6) Adsorption. THM precursors and many other dissolved organic compounds may be removed from water by adsorption. Most applications of this methodology have employed either granular or powdered activated carbon, but synthetic media have also been used (Boening, Beckmann, and Snoeyink 1980; Cannon and Roberts 1982; Suffet 1980; Krabill 1981; and Weber and van Vliet 1981). Granular carbon is usually used in pressure operated contactors similar to ion exchange units, while powdered carbon is mixed with the water and subsequently removed by settling and filtration. Synthetic media are usually employed in the same manner as granular carbon.

b. Other organics. Any of the thousands of organic chemicals used daily in industrial, commercial, municipal, and domestic activities may wind up in a public water supply. The sheer numbers and diversity of the possible organic contaminants make the problem of removing them a difficult one. The current list of synthetic and volatile organic carbons is quite extensive and continues to grow. The techniques mentioned in a(1), a(2), a(4), a(5), and a(6) above are useful in dealing with many organics other than the trihalomethane precursors (Dyksen and Hess 1982 and Love and Eilers 1982). However, the nature of organic contamination is such that no removal process or method should be included in a water system design until the contaminants and their sources are identified, and the method or process has been tested at the laboratory or pilot

scale and proven effective. Maximum contaminant levels are subject to enforcement; therefore, it behooves the designer to contact the appropriate drinking water regulatory agency for discussion and current requirements. Many times the experience of regulators with specific systems and contaminant problems is exceedingly useful.

6-12. Membrane Technologies

Recent improvements in membrane technologies have allowed more versatile applications of drinking water treatment for small systems. Previously, more or less, membranes were used in drinking water treatment for desalting brackish water and seawater. Membranes are finding more applications in filtration and disinfection compliance. Beside reverse osmosis (RO) as discussed in paragraph 6-9, "Total Dissolved Solids Removal," engineers classify membranes in three additional categories: microfiltration (MF), ultrafiltration (UF), and

nanofiltration (NF). Depending on the water treatment need, membranes have a particular processing function. Membrane systems can be used for removing particles, microorganisms, natural and synthetic organic matter, and inorganic chemicals. Though the processes and equipment operations have improved over the years, whether or not to employ a membrane unit operation remains dependent largely on the treatment compliance criteria, chemical and physical condition of the source water, and whether the operations and maintenance personnel are adequately staffed and trained. Better understanding of membrane filtration for water treatment is required before universal application can be assumed. Among the considerations for additional research include pretreatment and membrane fouling, precursor removal, and preoxidation issues. However, as the technology and systems continue to improve, membrane technology may offer an attractive alternative for treatment and should be considered in the overall evaluations.